IMPROVING THE EFFICIENCY OF LIME BURNING ANNULAR SHAFT KILN BY GAS RECIRCULATION

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Abstract. Older annular shaft kilns for lime burning that have been in operation for several decades may start to operate continuously at an excessively high excess air ratio. Because of this problem, stack losses increase, the kiln efficiency decreases, and fuel consumption increases. One may encounter the dilemma of how to operate the kiln at an optimal air excess ratio. Due to excessively high temperatures in the combustion chambers at optimal air excess ratio, the flame must be cooled with a greater amount of relatively cold secondary air. This results in greater heat loss with the exhaust kiln gas (stack losses), greater fuel consumption and lower kiln efficiency. The effects of increasing air excess ratio during the process of lime burning in an annular shaft kiln are specifically analysed. The paper deals with the the case from practice. The remodelled annular shaft kiln is presented in which the air excess ratio is reduced to its optimal level by using the recirculation of waste gas. The waste flue gas are cooled in recuperator and injected into the combustion chambers. That measure also reduces the stack losses, while the temperatures in the combustion chambers remain within the permissible range. The final result is the reduction of specific energy consumption for lime burning. The paper presents the results of measuring, diagrams, schemes as well the results of calculations.

Key words: Annular shaft kiln, Lime burning, Gas recirculation, Air excess ratio, Fuel Savings.

1. INTRODUCTION

Older annular shaft kilns that have been in operation for several decades may start to operate continuously at an excessively high excess air ratio. Because of this problem, stack losses increase, the kiln efficiency decreases, and fuel consumption increases. The reason for permanent operation at an increased air excess ratio is that at lower air excess ratios, which are more optimal for combustion, excessively high temperatures start appearing in the combustion chambers. Several factors may cause this phenomenon, the most common being a different composition of the raw material (limestone) and deteriorating heat insulation of the kiln, which causes greater heat loss and increases the energy input. Excessively high temperatures in the combustion chambers cause damage to the kiln lining, contamination of the surface of the stone, particularly with clay, which can fuse one lump to another and causes the formation of lumps of clay, which also can cause fusion. Therefore, some smaller lumps of lime become overburnt causing a nonuniform lime quality. In order to prevent temperatures in the combustion chambers from exceeding the permissible levels, the flame in the combustion chamber is cooled with a greater amount of secondary air. The air excess ratios are therefore higher than necessary for optimal combustion. At higher air excess ratios, the temperature in the combustion chamber is reduced, the mass flow of gases in the kiln increases, and heat loss with the exhaust kiln gas at the kiln outlet increases. The higher mass flow of kiln gases at the kiln outlet also increases electrical energy consumption, due to blowers needed for transportation of the exhaust kiln gas. The principle of operation of annular shaft kilns for lime burning is presented in many publications (Oates, 1980), so it will not be discussed here. The energy flows and energy balance in counterflow lime burning in shaft kilns are well presented by Ruch (1981) and Thomas (1981, 1992). A very extensive recent study of problems related to counterflow lime burning is given by Schwertmann (2004). Recently, the influence of vertical temperature profile in an annular shaft kiln on the calcination process has been experimentally measured and analysed by Senegačnik (2007). Since Beckenbach's invention of annular shaft kilns in the 1960's, quite a few successful adaptations to suit various fuels and raw materials (lime types) have been introduced (Beckenbach et al., 1982, Zeisel 1996, Arnold, 1997, 1999, Opiz, 1984). This paper presents the remodelling of an annular shaft kiln that enables a reduction of the air excess ratio to optimal levels. Exhaust kiln gas recirculation and their injection into burners instead of (or in combination with) secondary air enables the desired reduction of the air excess ratio without exceeding the permissible temperatures in the combustion chambers. This results in an increase in the kiln's thermal efficiency and a reduction in fuel consumption. The presented technical solution is patent-protected.

2. IMPACT OF AIR EXCESS RATIO

Changes in air excess ratio have an effect on processes in which the internal energy of hot flue gas released by combustion is used as the energy source. In general, such processes exhibit varying degrees of sensitivity to changes in air excess ratio. Lime burning in annular shaft kilns belongs among processes that are more sensitive to changes in air excess ratio, e.g. processes in burning devices in which a certain working fluid is heated or evaporated (e.g. steam boilers). The reason for this lies primarily in the chemical nature of the lime burning process, the decomposition of $CaCO3$.
The influence of the air excess ratio on lime burning is presented schematically in Fig. 1. This shows the variation of kiln gas enthalpy (expressed in kilojoules per kilogram of quick lime CaO) with temperature. To simplify the explanation of the influence of the air excess ratio on the process of lime burning in an annular shaft kiln, it is assumed in Fig. 1 that combustion in the kiln is one stage, as is the case with long rotary kilns for example, and not two stage, which actually occurs in annular shaft kilns. As a starting point, it is assumed that the kiln consumes 3980 kJ of heat per kilogram of product (the raw material contains 95% $CaCO3$, 2.5% $MgCO3$ and 2.5% other substances). Natural gas (98% methane) is used as fuel, and its combustion takes place at an air ratio of 1.1. Line A presents the starting enthalpy of the specific mass of flue gases resulting from combustion which Is needed to make 1 kg of the product – lump quick lime. The necessary energy for calcination is taken from hot flue gas directly after combustion, Line A. During the calcination process, $CO2$ is

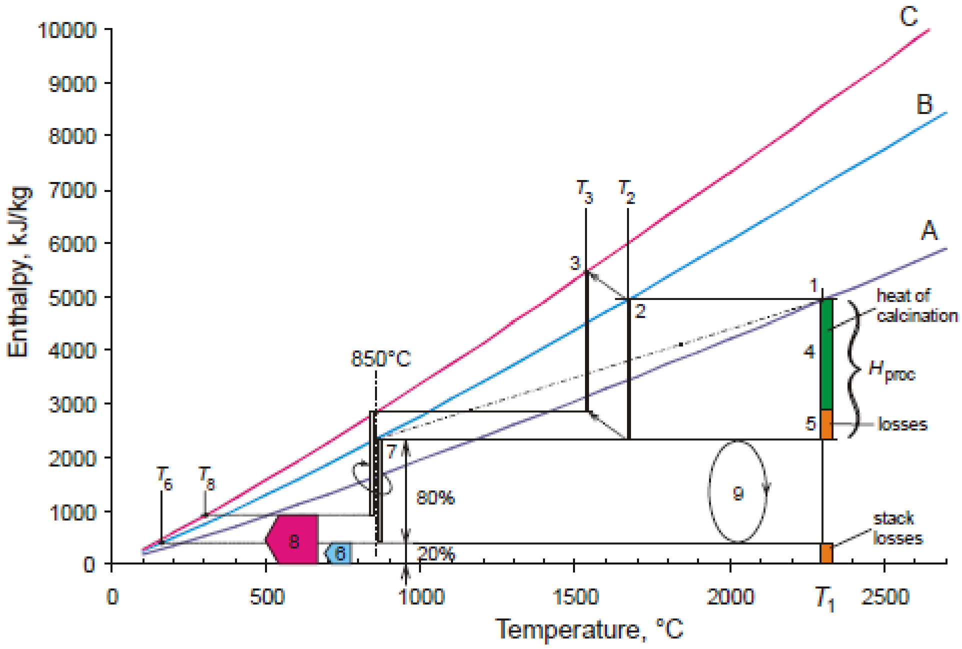

Figure 1. The effect of air excess ratio on counterflow lime burning.

released, and as a result the specific mass of flue gases increases. The characteristic variation of increased specific mass of flue gases after completed calcination is shown by Line B. It was found experimentally that in an annular shaft kiln, calcination starts at a temperature of ≈850°C (Senegačnik, 2007). Since the process is counterflow, calcination begins where the specific mas of gases is the greatest and their temperature is the lowest, i.e. at point 7 on Line B. The high temperature heat needed for lime burning in a kiln Hproc is the total sum of heat needed for the chemical reaction, i.e. calcination (decomposition of CaCO3 to CaO and CO2), which is indicated by green column 4, and heat consumed for radiation losses and some other losses indicated by orange column 5. If the value of Hproc is added to the initial value in point 7, the obtained sum on Line A corresponds to point 1 for adiabatic flame temperature T1. The enthalpy between points 1 and 7 is available for calcination and for covering heat losses. In a real process, the temperature of gas is always lower than the adiabatic flame temperature because combustion takes place in two stages, with a mixture of fresh air, already released flue gases and CO2 from calcination. In Fig. 1, this is taken into account in a simplified way by transferring point 1 from Line A horizontally to Line B, point 2. The temperature in point 2 (T2) therefore represents a certain hypothetical temperature in which gases with composition B would contain enough energy for entire calcination and for covering losses (this simplification does not affect the final result and is therefore permissible). In the event that temperature T2 exceeds the permissible temperature in the combustion chamber, the flame temperature in point 2 should be reduced. This is done by adding more cold combustion air, i.e. by increasing the air excess ratio. Line C corresponds to this increased specific mass of flue gases (after calcination). The necessary energy supplied for the process Hproc has remained unchanged in spite of a higher air excess ratio, and so is the final kiln gas temperature after calcination, which is still at 850°C. If the corresponding line transpositions are entered in Fig. 1, point 2 moves to point 3 and temperature T2 decreases to T3. By increasing the air excess ratio, one can therefore always achieve a sufficient temperature reduction in the combustion chambers. Let us now examine the consequences of increasing the air excess ratio for stack losses. Start with point 7 on Line B. In an annular shaft kiln, it is possible to recuperate 75-80% of heat from the preheating zone to the process (Thomas, 1981, Schwertmann, 2004), as indicated by no. 9. In the preheating zone, kiln gases heat the limestone and the driving air, while in the cooling zone the hot lime formed heats a portion of the combustion air.

The waste heat flow, no. 6, leads ≈20-25% of the energy flow that enters the preheating zone into its surroundings. In the case of an increased air excess ratio, energy at entry to the preheating zone increases correspondingly, but only the same amount of heat as before can be returned to the process. The result is that the energy flow to the surroundings, no. 8, increases strongly, and at the same time the flue gas temperature at the outlet from T6 to T8 also increases. The reason for such a strong influence of the air excess ratio on heat loss during lime burning therefore lies in the very nature of the process. Figure 2 shows the energy balance for additional air excess and explains why heat loss increases so drastically. Additional air, which is actually excess cooling air of the inner cylinder, needs to be heated by fuel from ≈200°C to the adiabatic flame temperature T1, after which only heat to 850°C is used for calcination, and the remaining heat is useless for the lime burning process. The process itself does not allow for other variants.

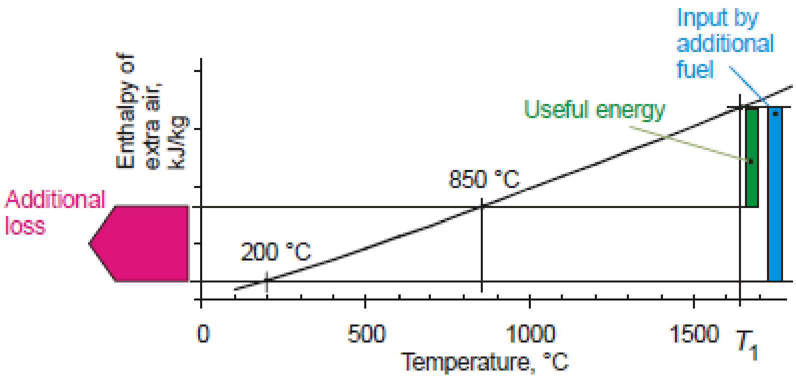

Figure 2. Air excess balance.

3. SYSTEM FOR KILN GAS RECIRCULATION

A schematic of an annular shaft kiln with kiln gas recirculation is shown in Fig. 3. The main idea and the principle of gas recirculation is that the flame in the combustion chambers is cooled with the exhaust kiln gas instead of additional amounts of secondary air. An additional recirculation driving blower is required, marked as D in Fig. 3, as well as additional distribution conduits, marked as E. The mixing of recirculated gas and secondary air takes place before their injection into burners. By using regulating flaps positioned on the conduits before the burners, Fig. 4, it is possible to achieve any ratio of recirculated gas to secondary air. Due to the presence of dust in recirculated gas, the measurement of recirculated gas flow was done using the Venturi nozzle. Gas recirculation has the following features:

- Optimal air excess ratios for the selected fuels are achieved, which leads to a reduction of stack losses;
- The exhaust kiln gas for recirculation can be taken from any point of the outlet conduits, but in order to maximise energy savings it is best to take the exhaust kiln gas from a place having the highest temperature, i.e. from the recuperator outlet, where the gas temperature ranges between 350°C and 400°C;
- Increased thermal efficiency of the kiln;
- Lower temperature in the combustion chambers;
- Enables a higher burner's heat power at a lower flame temperature;
- Due to a lower oxygen concentration in the combustible mixture, the combustion time increases and local thermal loads in the combustion chambers decrease;
- Switching between operation with or without recirculation is simple.

The presented recirculation method can be used on all industrial kilns in which excessively high temperatures are reached during operation at optimal air excess ratios. These high temperatures need to be reduced either by increasing the air excess ratio or by cooling the flame with air.

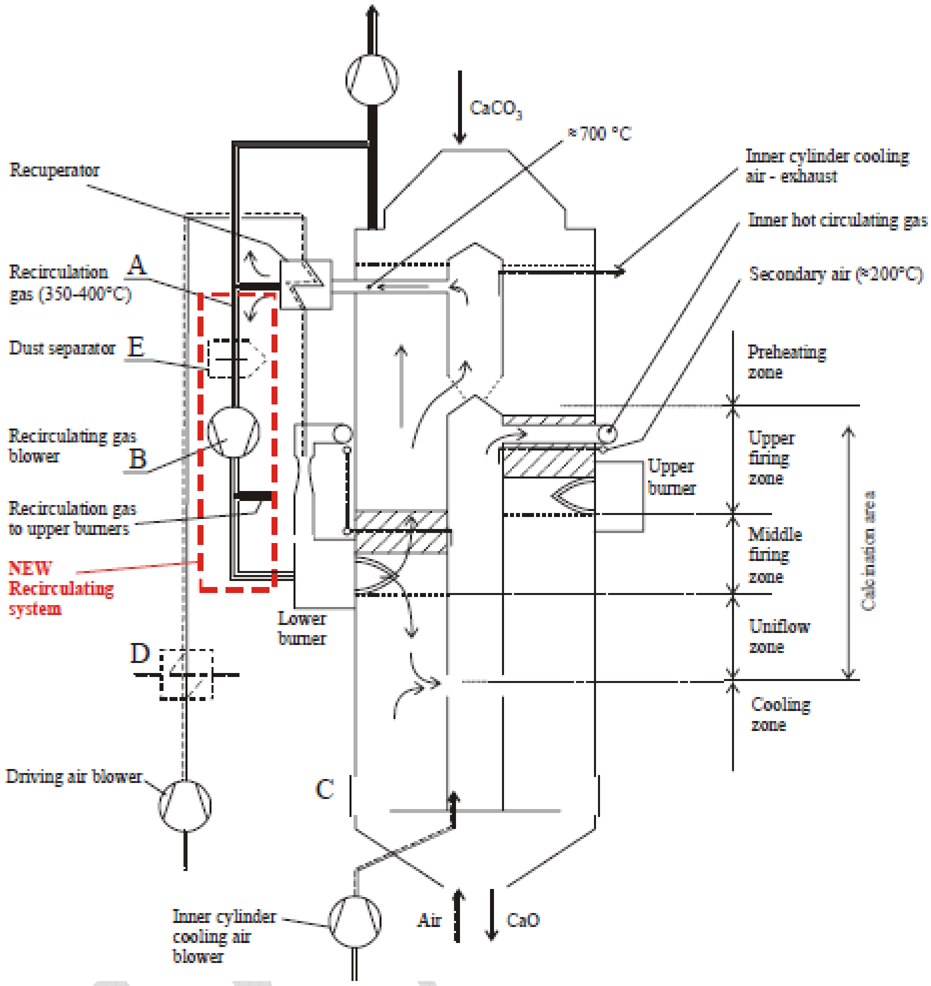

Figure 3. Schematic of an annular shaft kiln with gas recirculation.

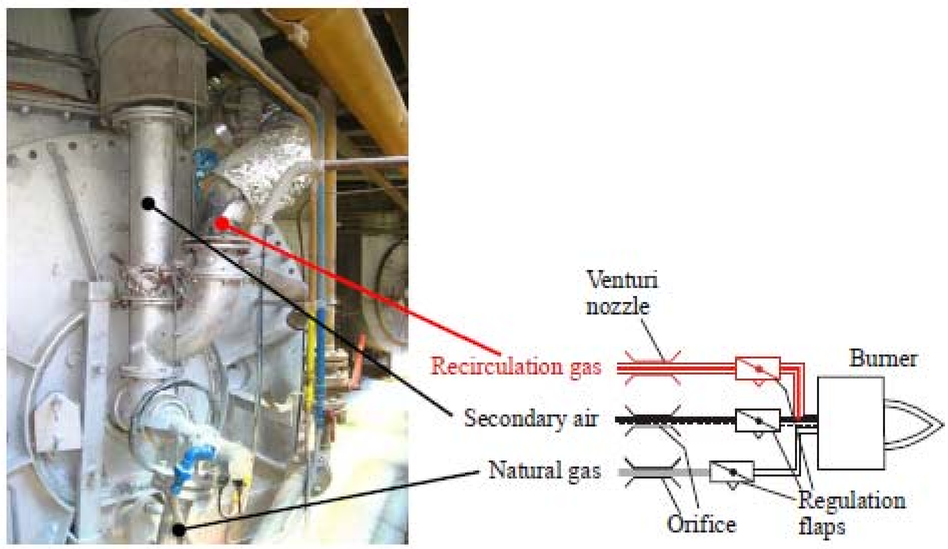

Figure 4. Recirculation on the lower burner.

3.1 Applications of gas recirculation

Figure 5 shows the variation of dry kiln gas composition at the kiln outlet with recirculation in effect and gradual replacement of secondary air with recirculated kiln gas. The kiln has 8 burners, i.e. 4 lower and 4 upper burners and the ratio of kiln gas fed back from the recuperator to the total kiln gas is ≈ 1/3. The kiln load is 150 tons/day. The air excess ratio is 1.46 and natural gas (98% methane) is used as fuel.

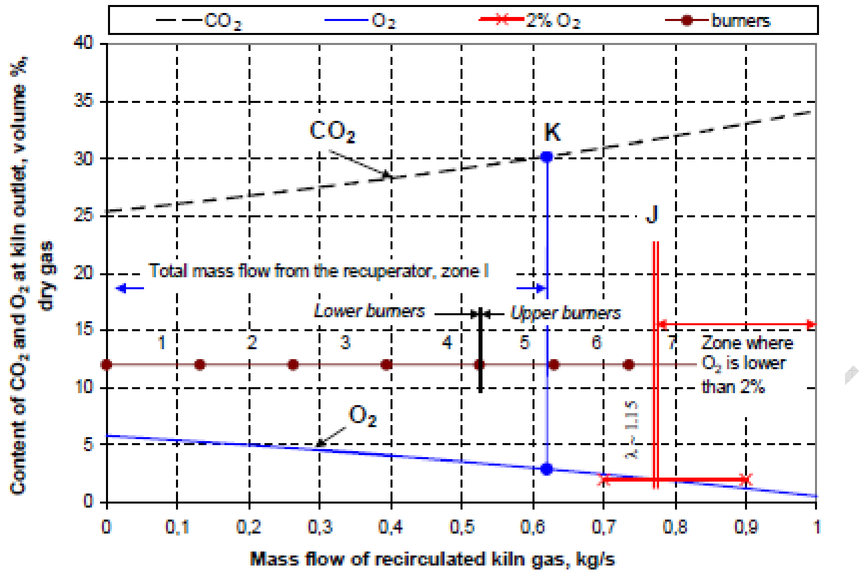

Figure 5. Conditions during kiln gas recirculation.

Figure 5 shows two lines, the upper one for CO2 and the lower one for O2 in a exhaust dry kiln gas. In the case where secondary air is replaced with recuperator gas, the O2 concentration decreases from the initial level of 5.8% and the CO2 content increases. Zone I in Fig. 5, which ends with line K, describes the case where the total amount of kiln gas from the recuperator is recirculated and the oxygen content in the kiln gas is reduced to ≈3%. As can be seen from the Figure, in this case all of secondary air is replaced in all lower burners and in one upper burner. In principle, the recirculation mass flow can be further increased until the oxygen content falls down to ≈2%, line J, which is also the value recommended in literature (Schwertmann, 2004, Beckenbach et al., 1982, Zeisel, 1996).

3.2 Operation with recirculation

When our kiln was actually run with gas recirculation, it turned out that it is unnecessary to replace the entire mass flow of secondary air. The desired effect of lowering the air excess ratio was achieved already by replacing smaller amounts of secondary air with recirculated gases. The reason for this lies primarily in the fact that instead of air, the fuel (natural gas) in the burner is dispersed with recirculated gas, which has a low oxygen content. This slows down combustion and the flame temperature decreases. The air excess ratio therefore decreases more quickly than in the case of computationally identical mass flows in Fig. 5. The reduction of air excess ratio at actual operating is presented in Fig. 6. The kiln load was 175 tons/day and actual air excess ratio ≈1.3. By total replacement of secondary air with smaller amount of recirculated gas on the lower burners the air excess ratio was reduced from 1.31 to 1.18. The oxygen content in dry flue gas lowered from 4.2% to 2.7%. Achieved oxygen concentracion in exhaust gas permits further air ratio reduction and replacement of the secondary air at upper burners.

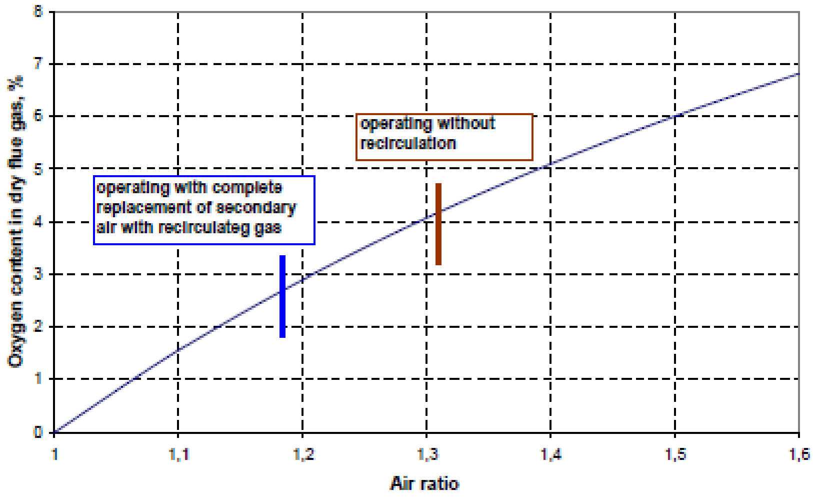

Figure 6. Air ratio reduction by recirculation operation.

It was found for the upper burners, where the local air excess ratio is ≈0.5 (local air ratio for lower burners are ≈1.8), that complete replacement of secondary air with recirculated gas is not possible because of the appearance of carbon monoxide in the exhaust kiln gas. Kiln operation with a lower amount of recirculated gas vs. secondary air has the following thermodynamic effects:

• Due to the smaller amount of ballast air, a smaller amount of kiln gases needs to be heated to reach the process temperature.

• Recirculated gases have a temperature of between 350°C and 400°C (at the recuperator outlet), i.e. higher than the secondary air, which has a temperature of ≈200°C. Because of the higher temperature, less energy is consumed for heating gases to process temperature, which leads to fuel savings.

• The excess amount of secondary air which is released to the surroundings and remains unused increases, thus increasing heat loss with excess secondary air. The energy of excess secondary air and cooling air from the kiln top (upper part of inner cylinder) can be beneficially used if these two flows are united and their energy is transferred to the driving air in an additional heat exchanger (element G in Fig. 3).

• The outlet temperature of kiln gases is lower because in the preheating zone the same amount of stone is now heated with a smaller amount of gas.

4. FUEL SAVINGS

In order to confirm fuel savings during kiln operation with recirculation, kiln measurements were performed at kiln load of 150 tons/day. In the initial phase of measurements, a recirculation blower was installed and a recirculation conduit to lower burner no. 2. Several trial operations were conducted, during which certain important parameters were measured and registered, such as differential pressure of natural gas at the measuring orifice of lower burner no. 2, as well as the temperatures of recirculation gases and secondary air. In order to analyse the CO2 content of quick lime, samples of lump quick lime were taken once daily, all of one size of ≈90 mm, from the 4 sampling or observation openings on the kiln, at location H in Fig. 3. For samples taken at door no. 2 located vertically under burner no. 2, it is assumed that they have travelled past burner no. 2 and were influenced by recirculation. Figure 7 presents the residual CO2 content in lump quick lime samples taken during kiln operation, with and without recirculation. As indicated by the lines, introduction of recirculation at lower burner no. 2 had no effect on the CO2 content in lump quick lime samples taken at door no. 2, as the highest values were actually achieved during normal operation. Analogously, it can be

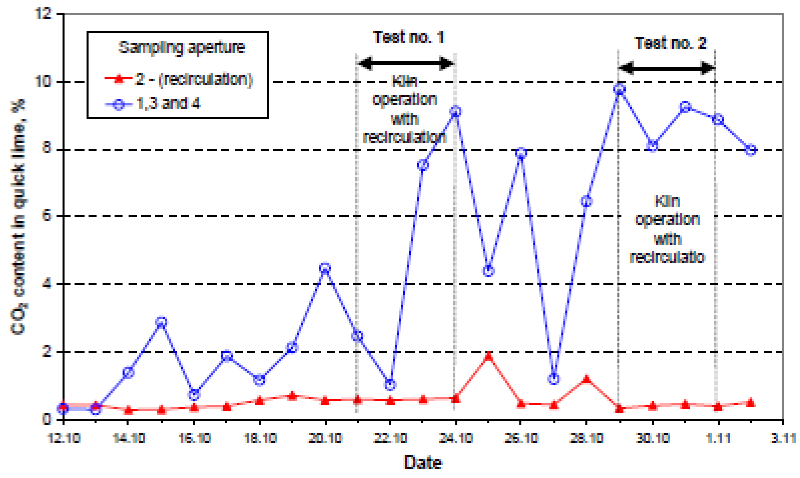

Figure 7. Residual CO_2 content in lump quick lime.

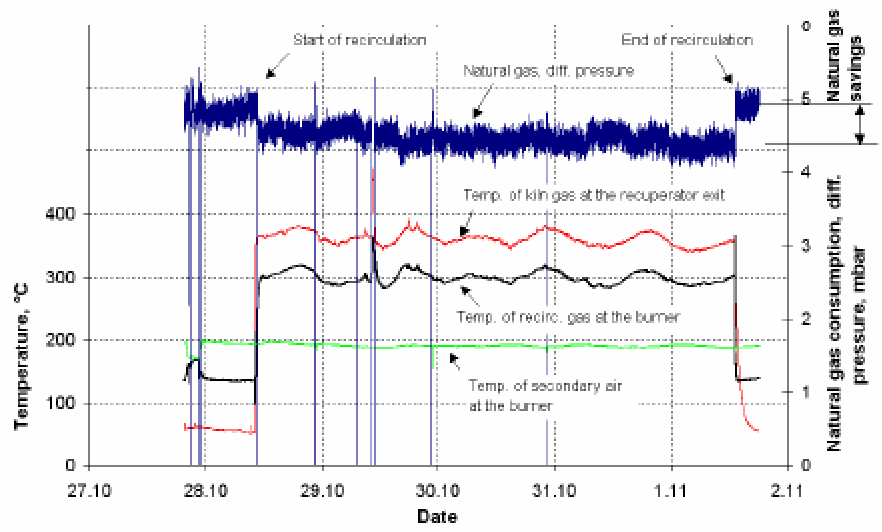

Figure 8. Recirculation parameters during test no. 2.

said that adding of recirculation also had no effect on the average value of CO2 in other samples (doors 1, 3 and 4), as CO2 values were high also during operation without recirculation. The essential reason for introducing kiln gas recirculation is to save fuel. Figure 8 shows the operating parameters during test no. 2. As can be seen in the Figure, between the time of its collection beyond the recuperator and its injection into the burner, recirculated kiln gas was cooled by 50°C on average as a result of the slightly inferior, improvised thermal insulation of the conduits in this first prototype version. In spite of this, the temperature of recirculated gas just before burner no. 2 was 100°C higher on average than the temperature of secondary air at the next burner, no. 1. In order to determine the level of fuel savings, the differential pressure of natural gas at the measuring orifice was registered for lower burner no. 2, see upper line in Fig. 8. The course of the line clearly shows the beginning and the end of operation with recirculation, as well as direct fuel savings during operation with recirculation. The fuel savings (only for lower burner no. 2) measured during the initial part of the test amounted to 3.2%, and at the end of the test to 4.6% compared to the kiln's usual settings. Daily kiln operation reports also showed that the temperature in the combustion chamber no. 2 decreased by ≈30°C during recirculation compared to temperatures during normal operation. Due to a higher dust content in recirculated gas, a dry particulate scrubber was installed before the recirculation blower, marked as F in Fig. 3.

5. CONCLUSION

During the operation of annular shaft kilns for lime burning, the problem of continuous operation at excessively high air excess ratios is often encountered. In cases where the air excess ratio is adjusted to the optimal level, temperatures in the combustion chambers may exceed the permissible values. For sustained operation, the flame is cooled with an increased amount of air. It was found that the process of lime burning in annular shaft kilns is more sensitive to increases in air excess ratio than are processes in a steam boiler. Operation at an excessively high air excess ratio is not cost-efficient due to significantly greater stack losses or higher fuel consumption. The air excess ratio can be reduced to the optimal level without increasing temperatures in the combustion chambers. This is done by cooling the flame with exhaust gases instead of with secondary air. Recirculation gas is collected at the recuperator outlet. An additional recirculation blower for recirculation gas needs to be installed on the kiln, as well as distribution conduits leading to the burners and including control flaps. Recirculated gas is then injected into the burners at an appropriate ratio to secondary air. Burner operation with recirculation causes lower flame temperatures and reduces the rate of combustion, which prolongs the flame duration. When dust is present in the recirculation gases, formation of deposits on the combustion chamber walls can be intensified, necessitating removal of the maximum possible amount of dust using a mechanical separator. The most important result of operating an annular shaft kiln with recirculation is the reduction of the air excess ratio to the optimal level with a resulting reduction in stack losses. Fuel savings depend on the level of air excess ratio reduction at the lower burners and may reach up to 5%. With recirculation, it is possible to achieve additional increases in kiln efficiency by transferring heat from excess secondary air and cooling air from the kiln top onto the driving air, which is done in an additional heat exchanger. This measure assures at least a further ≈1% of additional total fuel savings. The effect that recirculation may have in terms of a possible decrease in lime quality was also determined by analysing the CO2 content in lump quick lime. A few intervals of kiln operation lasting several days were performed, with and without recirculation, and it turned out that recirculation does not increase the CO2 content of lime, so its quality remains unchanged.

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